LPCR WIND VECTOR PROFILE MODE FOR PRECISION AIR DELIVERY IN ADVERSE WEATHER

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ABSTRACT

The wind *vector* field at points in space about the expected fall trajectory of airdrop cargo can be estimated with a modified AN/APN-241 RADAR (Low Power Color RADAR) for improved point of delivery accuracy. Performance is based on the principles of Doppler meteorological RADAR, and sensitivity will extend into planetary boundary layer altitudes with so-called meteorological "Clear Air Reflectivity" opportunities. Evidence of mesoscale β convection in light reflectivity during flight test will be analyzed to substantiate performance expectations.

1.0 INTRODUCTION

The purpose of this paper is to describe the techniques that may be employed to remotely estimate wind speed and direction with modern coherent airborne RADAR. The technology roadmap for sensing winds for precision air delivery has included LIDAR, but intervening atmospheric conditions and weather can compromise LIDAR performance. The AN/APN-241 RADAR, now standard equipment on the C130 and C130-J production aircraft, has existing capabilities to sense the line-of-sight Doppler return of wind blown particles as a distribution over a 3 dimensional volume of scan. The mode suite includes warning of hazardous windshear at low altitudes arising from downdraft and divergence disturbances from velocity structures such as gust fronts or microbursts, often with vanishing precipitation. This is an inherent capability to produce Doppler maps of reflective winds at a sequence of elevation cuts, and it remains to analyze the signature of the Doppler winds to estimate the wind vector field as a function of altitude in the differing geometries supporting the operational requirements of precision airdrop.

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This work is funded by contract through the Geophysics Directorate of the Air Force Research Labs by the Office of Scientific Research as part of the *New World Vistas* program[1]. The contract (F19628-98-C-0027) was awarded to Northrop Grumman and Lockheed Martin for a proposed statement of work valued at $ 1.19 M over a period of 42 months to demonstrate and validate the use of the off-the-shelf AN/APN-241 RADAR to measure three dimensional range-resolved wind fields in adverse weather as part of an all weather precision air delivery (PAD) system. This included delivery of a prototype mode for flight test demonstration in year 2002. This program has proceeded on an incremental funding basis.

In the context of precision air delivery, adverse weather is meant to imply compromised visibility by precipitation. Even if LIDAR technology were soon to mature into a practical and affordable sensor for a military cargo aircraft, it would not be expected to operate in all weather conditions. The low-cost, low-power AN/APN-241 X-band air transport RADAR is already on the aircraft for weather avoidance. Airdrop missions are constrained to safety of flight considerations and will continue to avoid strong rain cells, squall lines, or thunderstorms. Unlike other air transport weather avoidance RADARs, the AN/APN-241 has been intrinsically designed for noise limited performance in lookdown geometries. It can continue to operate on principles of coherent meteorological RADAR to measure and interpret the spatial distribution of Doppler returns in forward (remote) looking geometries from the altitude of the airdrop to the dropzone.

This paper is organized to review air cargo drop mission requirements for wind vector information and relate the techniques of range resolved Doppler wind signature interpretation from the literature on meteorological RADAR. These techniques are being demonstrated with FAA meteorological NEXRAD and TDWR RADARs in non-precipitation planetary boundary layer phenomenon, that is, so-called "clear air reflectivity", to forecast terminal winds to mitigate air traffic delays. The paper will inspect some amplitude and Doppler data obtained in flight under representative precipitation conditions and provide a visualization interpretation.

2.0 WIND INFORMATION FOR THE AIR DROP MISSION

Wind information is utilized in an airdrop to construct a wind drift range vector [2](see figure 1). This laterally offsets the fly-to point (computed air release point) for the drop from the coordinates of the impact point at the drop zone. Information entered into the flight plan for each drop zone includes coordinates for ingress and egress waypoints. The direction for the flight plan leg to the computed air release point is also specified, but the flight plan computer constructs the turn points. In general, the drop altitude, waypoints and desired aircraft direction are produced by the air crew from tactical considerations of the cargo, the drop altitude, the sequence of the other events planned for the mission, perceived threats, etc. Although wind might be a slight factor in planning, information about winds for constructing the flight plan is committed to use at the waypoint prior to the constructed turn point.

The turn point is constructed by the flight management computer to allow time for the aircraft to coast down to the speed required for the cargo drop. This will vary somewhat depending on the cargo, e.g. pallet or personnel. The range from the aircraft to the drop zone will depend somewhat on the winds and the selected course, but a range of perhaps 15 - 20 NMI. for measurement of the ballistic wind profile about the drop zone prior to the initial waypoint seems adequate to update the flight plan for the respective dropzone with measured wind data just prior to the turn on to the first leg dependent on that information.

Air drops are currently most often conducted using flight plans generated prior to take-off with forecast winds, often hours old before the flight even takes off. Some airdrops are conducted using

[1] McCall, G.H., and Corder, J.A., *New World Vistas,* "Air and Space Power in the 21st Century", from http://web.fie.com/htdoc/fed/afr/sab/any/text/any/vistas.htm

[2] AFI 11-231, 1 JUN 1998, *Flying Operations, Computed Air Release Systems Procedures* from http://afpubs.hq.af.mil, http://afpubs.hq.af.mil/pubsforms/pubs/af/11/11023100/11023100.pdf

estimates of the winds at the altitude of the cargo aircraft, with dropwindsonde profiles, or are supplied with near-real time reported estimates of winds at the drop zone. However, the mission survivability of even principally humanitarian aid drops in Bosnia would have been compromised by tactics advertising to anti-aircraft weapons the approach of a cargo plane or requiring a second pass over the drop zone.

The existing procedures for computation of the wind drift offset consider the effects of wind as a simple translation of a body falling in terminal velocity equilibrium at a constant rate. The translation may be broken into different segments for drops with free fall and chute deployed segments, but, for constant fall rate segments, the consequence is that integration of lateral translation velocity over time is equivalent to integration of the winds over altitude, so the pertinent information of the wind vector field spatial distribution is the *altitude averaged wind vector*.

Forecast winds or adjusted wind at aircraft altitude in general do not address *orographic* perturbations. For example, in Bosnia, many drop zones where specified along the sides of mountains, so that the cargo pallets would not land in or on heavily populated town centers of the valleys. Located on the sides of rugged hills or mountains, the winds local to the drop zone might differ considerably from mesoscale β meteorological forecasts by the channeling of the terrain or thermal air flow dominated by the relative heating and cooling of the countryside. Ridgeline effects have been cited as major cause of lost cargo.

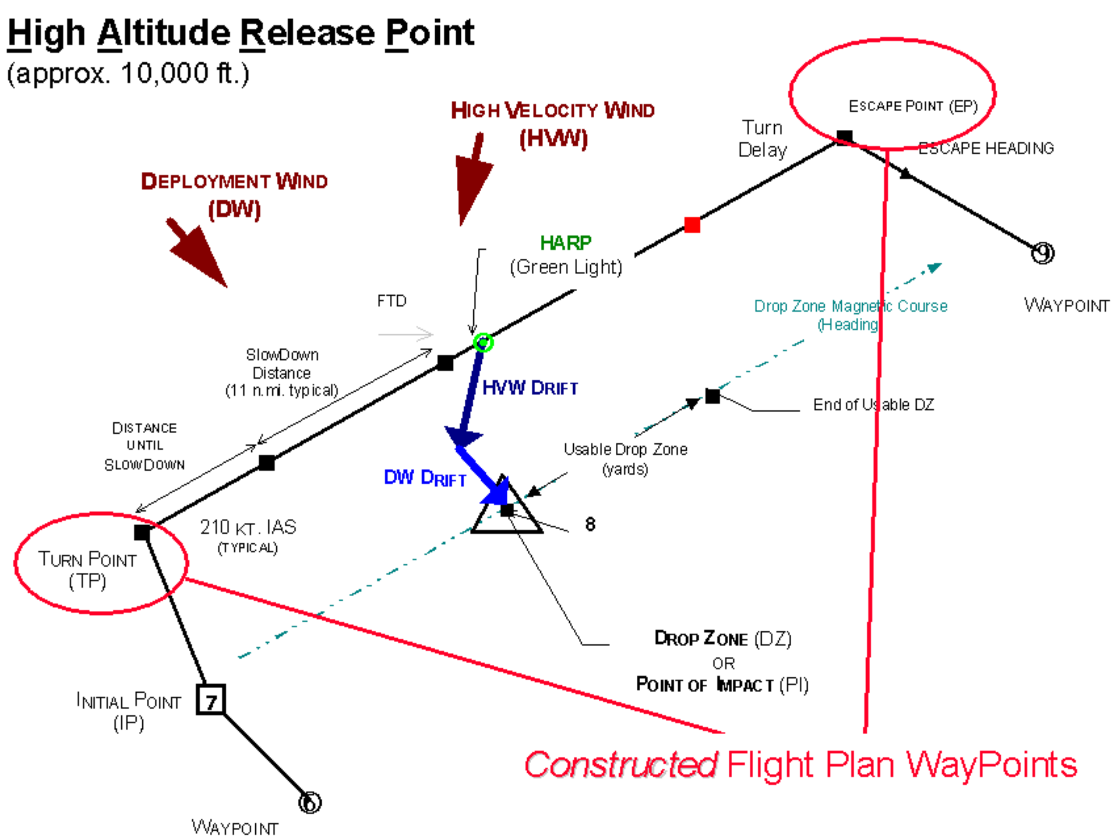

Figure 1 High Altitude Release Point (HARP) Flight Plan View

In the *New World Vistas* vision of the Army After Next (AAN)[3], precision air delivery is concerned with new methods and technologies for *point of use* delivery, including low cost guided parafoils with performance capabilities for deceptive offset drops and accurate delivery in a highly coordinated fashion to dispersed assets. Improved wind information supporting improved delivery precision may utilize an integration of sensing and rapid update to forecasting. The guidance of these new air drop technologies will require greater precision in the knowledge of the structure of winds along an expected trajectory to realize the benefits of low cost, drop offset, and accuracy.

3.0 WIND VECTOR ESTIMATION WITH DOPPLER MEASUREMENTS

Wind vector estimation based on interpretation of spatially distributed Doppler measurements is an established art. The so-called Velocity Azimuth Display System[4] (VADS) technique is little more than the observation that a full azimuth revolution by RADAR in a prevailing horizontal wind will produce a maximum Doppler shift in the direction of the incoming wind. In principle, it states a simple mathematical model or hypothesis for the structure of the wind, i.e. constant in direction and magnitude over space. The unknown coefficients for direction and speed are determined by an azimuth Fourier transform of the time record of Doppler velocity as a function of scan. It has been generalized from a simple homogeneous 2-D field to a 3-D linearly variable field. Wind vector estimation from Doppler measurements is, in principle, a regression problem for the unknown coefficients of a spatial model.

3.1 A BRIEF REVIEW OF THE LITERATURE

The acronym VADS initially meant a uniform 3 dimensional spatial model of uniform winds processed by an azimuth Fourier transform. The data is most often sampled in a conical scan about a vertical axis. Profiling RADARs, operating at VHF or UHF, can obtain sufficient backscatter from discontinuities in the index of refraction of air from intrinsic turbulence to measure the altitude profile of winds to high altitudes.

Laterally remote sensing of the wind vector field utilizes the change of Doppler return over multiple lines-of-sight (LOS) of an azimuth scan or a series of azimuth scans to generate multiple equations to over-determine the unknown coefficients of a simple spatial velocity dependence (see figure 2). Generally, accuracy in these least mean square solutions will approach the mesoscale β winds and is limited by the presence of atmospheric turbulence or weather system boundaries.

The important operative in least mean square solutions is the number of independent equations. A three dimensional linear model of the winds will vary in Cartesian space as functions of x, y, and z and consist of 12 unknown coefficients. A single azimuth scan might easily produce hundreds of range gate x beamwidth resolution cells with Doppler measurements. But some gradient terms are coupled to the spatial variation of constant terms. This observation may first be attributed to Easterbrook[5], who analyzed horizontal wind divergence, stretching deformation, and shearing deformations. Horizontal vorticity, or the curl of the winds, geometrically manifests itself in an artificial cross beam component. He

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[3] R. Benney, "NWV-PAD for BG Lewis", 1 FEB 1999
rbenney@natick-emh2.army.mil

[4] Lhermitte, R.M. and D.Atlas, "Precipitation Motion by Pulse Doppler Radar", *Proc. Ninth Weather Radar Conf.*, Am. Meteorol. Soc., Boston, MA, 1961, pp. 218-223

[5] Easterbrook, C.C., "Estimating Horizontal Wind Fields by Two Dimensional Curve Fitting of Single Doppler RADAR Measurements", *Preprints 16th RADAR Meteorol. Conf*, 1974, pp 214-219

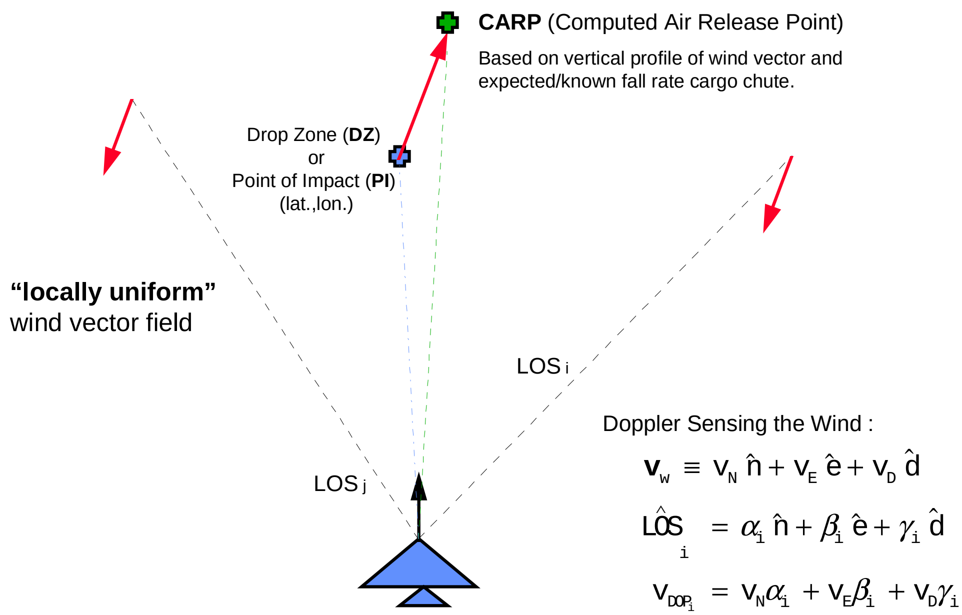

Figure 2 VADS Employs a Simple Model for Velocity as a Function of Spatial LOS Coordinates

defined a pseudo-vorticity as an artifact of the LMS solution that could be removed by model assumption of the vorticity or by knowledge of the transverse velocity component value at the modeling point (x_0, y_0, z_0). Generally, the wind vector components at the RADAR (0,0,0) will be known, but linking a remote analysis of wind data to the RADAR origin will force the averaging to become much less local in character.

Watdteufel and Corbin[6] analyzed single Doppler RADAR scan data in an attempt to process the data as a volumetric velocity sample, which they termed VVP, rather than the conical sample or area sample (Easterbrook), which they termed VARD, for an absence of vertical component or vertical gradient modeling. They solved Easterbrook's problem by conducting the linear hypothesis at the RADAR origin and simplified the number of unknowns by neglecting lateral gradients in the vertical component, which they termed locally stratiform situations. They sought to obtain accurate solutions for vertical components and divergence.

Doviak and Koscielny[7] addressed VVP for accurate divergence measurements under local approximation, that is, small sector scans. In particular, they addressed the statistical adequacy of the model through a sensitivity or alias matrix analysis of biases introduced by the neglect of certain model terms. From the analysis of adequacy bias, they concluded that the VARD model could not be relied upon without accounting for vertical gradients, and, furthermore, single scan information was insufficient to

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[6] Waldteufel, P. and Corbin, H., "On the Analysis of Single Doppler Data", *J. Appl. Meteorol.*, vol. 18, 1979, pp 532-542

[7] Koscielny, A.J., Doviak, R.J., and Rabin, R., "Statistical Considerations in the Estimation of Divergence from Single Doppler RADAR and Application to Pre-storm Boundary Layer Observations", *J.App.Meteorol.*, vol. 21, 1981, pp 197-210

determine all (i.e. vertical gradient) terms. For the model to distinguish vertical and horizontal derivatives, the analysis volume must include two or more elevation cuts. Horizontal and vertical gradient components could be resolved only if the data included equations with Doppler measurements independent in both elevation and azimuth. They concluded that (1) local approximations are practical if adequate unknown coefficients for the data are included and (2) data is collected over a range of independence. The Easterbrook problem of pseudo-vorticity was resolved by working out from the RADAR origin, i.e. the transverse component is allowed to vary in a piecewise linear fashion from the origin to the locale of analysis. Within the locale analysis, the transverse velocity component is known at the near range boundary. In their text book, Doviak and Zrnic[8] present results of mesoscale β frontal analysis at very long ranges, for analyzing thunderstorm formation by divergence, using locales constructed about the discontinuities of the front which agree with field measurements of the weather system.

The integrated terminal wind system (ITWS)[9] combines data on winds and conditions reported by aircraft, forecast models, with RADAR Doppler data to produce a gridded analysis of winds near an airport. The data contributed by the RADAR is used only on a point or resolution cell basis, but it can be combined with other data for the wind velocity at the field grid point, including other RADAR data, by multiple or dual Doppler analysis. The bulk of the data contributed in the integrated system comes from the ground based NEXRAD and/or TDWR RADARs operating in low scans within the altitudes of the planetary boundary layer in non-precipitation conditions. The boundary layer has significant vertical transport mechanisms to propel particles (insects, debris, pollen, seeds, etc.) to several thousand feet altitude. Opportunities of so-called "clear air reflectivity" are less pronounced in cool, dry conditions. For example, winds within the boundary layer at Kansas City, Mo. would almost always be measurable with reflectivity's greater than –5 dBz in the summer, but, in the winter, the reflectivity might rarely exceed +5 dBz.[10] Reflectivity and Doppler graphical data from NEXRAD operating in the so-called "clear air" mode is routinely available on the Internet.

Typical air transport weather RADAR have systems parameters which suggest noise limited detection ranges on volumetric particle distributions well below the levels of weather avoidance.[11]

4.0 AN EXAMPLE OF WIDE-SCALE LINEAR WIND DOPPLER SIGNATURE

The purpose of this section is to examine an instance of volumetric reflectivity against fairly homogenous winds to illustrate the interpretation of the signature of Doppler winds.

In 1993, MODAR 3000 was operating in the windshear mode a BAC 1-11 during an approach into National Airport, Washington, and DC. (The MODAR 3000 is a variant of the AN/APN-241composed of identical subassemblies, but with ARINC type antennas and interfaces configured for the commercial air transport market.) Part of its normal operation is the porting of data to an optional engineering display which allows monitoring of important processes. The Northrop Grumman windshear-warning mode employs a two elevation bar scan to construct a hazard hypothesis on a locally vertically extensive velocity structure model of divergent winds. The top elevation bar points above the horizon and the lower bar points ostensibly along the glideslope. The display data (see figure 3) included, from top to bottom, a color coded volumetric reflectivity azimuth x range display for the upper bar, a color coded Doppler wind map for the upper bar, respective reflectivity and Doppler wind maps for the lower bar, and various

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[8] Doviak,R and Zrnic,D., Doppler Radar and Weather Observations, Academic Press, New, pp 261-278

[9] Cole, R.E. and F.W. Wilson, "The Integrated Terminal Weather System Terminal Winds Product*", the Lincoln Laboratory Journal*, vol. 7, no. 2, 1994, p. 475 – 502, http://www.ll.mit.edu/AviationWeather/colewilson.pdf

[10] Biron, P.J., and Lee, T.S., "Microburst Outflow Reflectivity Distributions", MIT Lincoln Labs , memo received 14 June 1991, includes clear air reflectivity statistics

[11] RTCA DO-220, "Minimum Operational Performance Standards for Airborne Weather RADAR with Forward-Looking Windshear Capability", dated 15 JUN 1993, appendix B

constituents contributing to the hazard factor maps. The Doppler wind color palette spans from 15 m/sec headwinds (green is good) to –17 m/sec, tailwinds, in approx. 2 m/sec. steps.

The pilot's display of weather, which is ARINC color-coded, is shown is figure 4. The weather display shows wide spread ARINC green (LSB) broken with patches of no weather portrayed. That map is merely a different color palette of the upper bar reflectivity map in PPI format. The minimum reflectivity shown on an ARINC weather display is +23 dBz, so the upper bar reflectivity map, which has almost complete indication of amplitude above noise threshold, contains signals with volumetric reflectivity below +23 dBz.

The only available corroboration on the winds is the audio. The pilot remarks that there is wide spread light rain. The *in situ* measurement of winds at the aircraft is 17 kts. just about "on the nose".

This display shows a signature of widespread convective activity out to 10 NMI. directed somewhat from the right of the nose, increasing with altitude. Note that the color equivalent of the first shade of magenta is 8-10 m/s, which, at near ranges, is in good correspondence with the pilot's call. These displays are indicating a wind field signature of about 9 m/s headwind coming from just right off the nose.

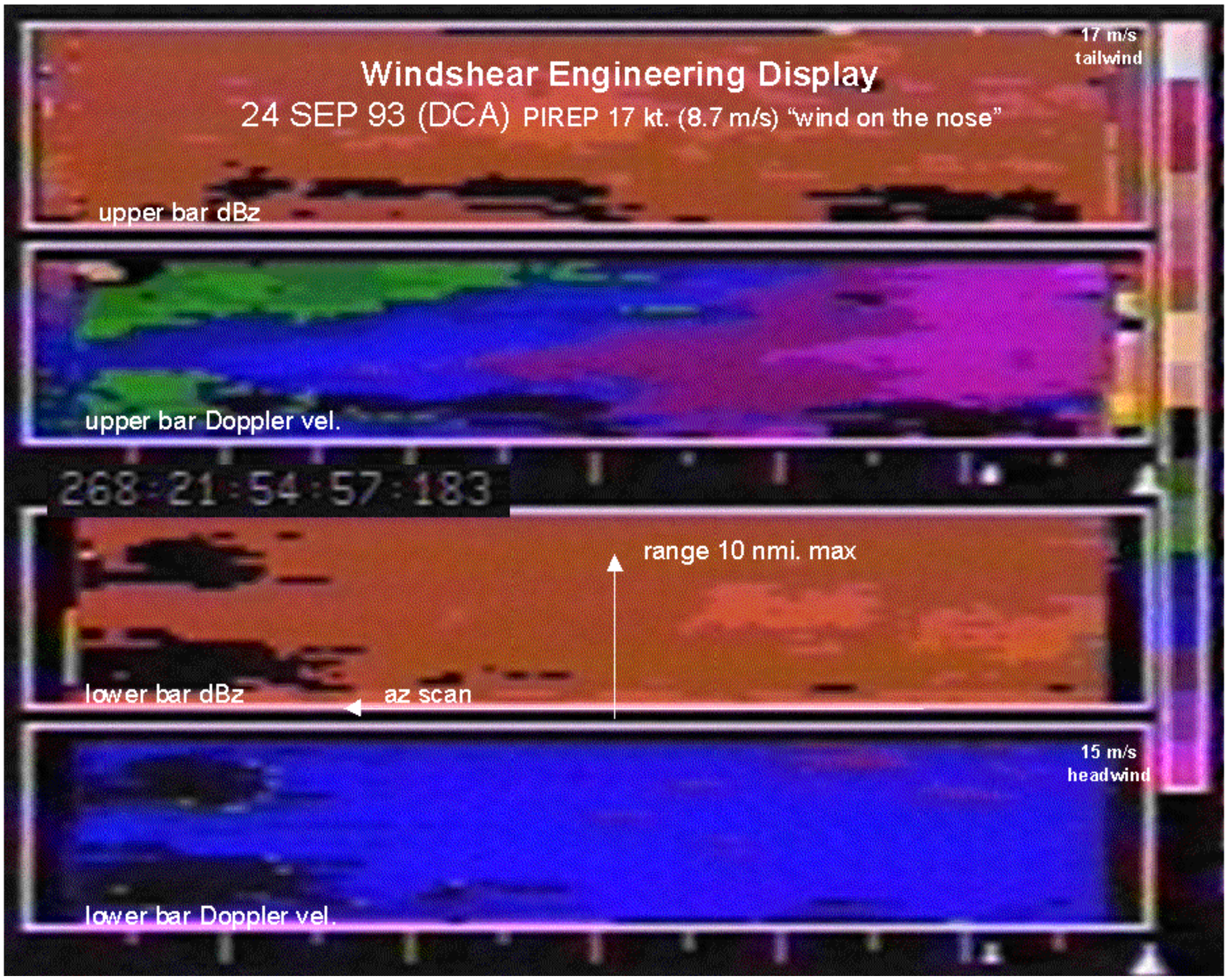

Figure 3. Example of Boundary Layer Uniform Linear Winds

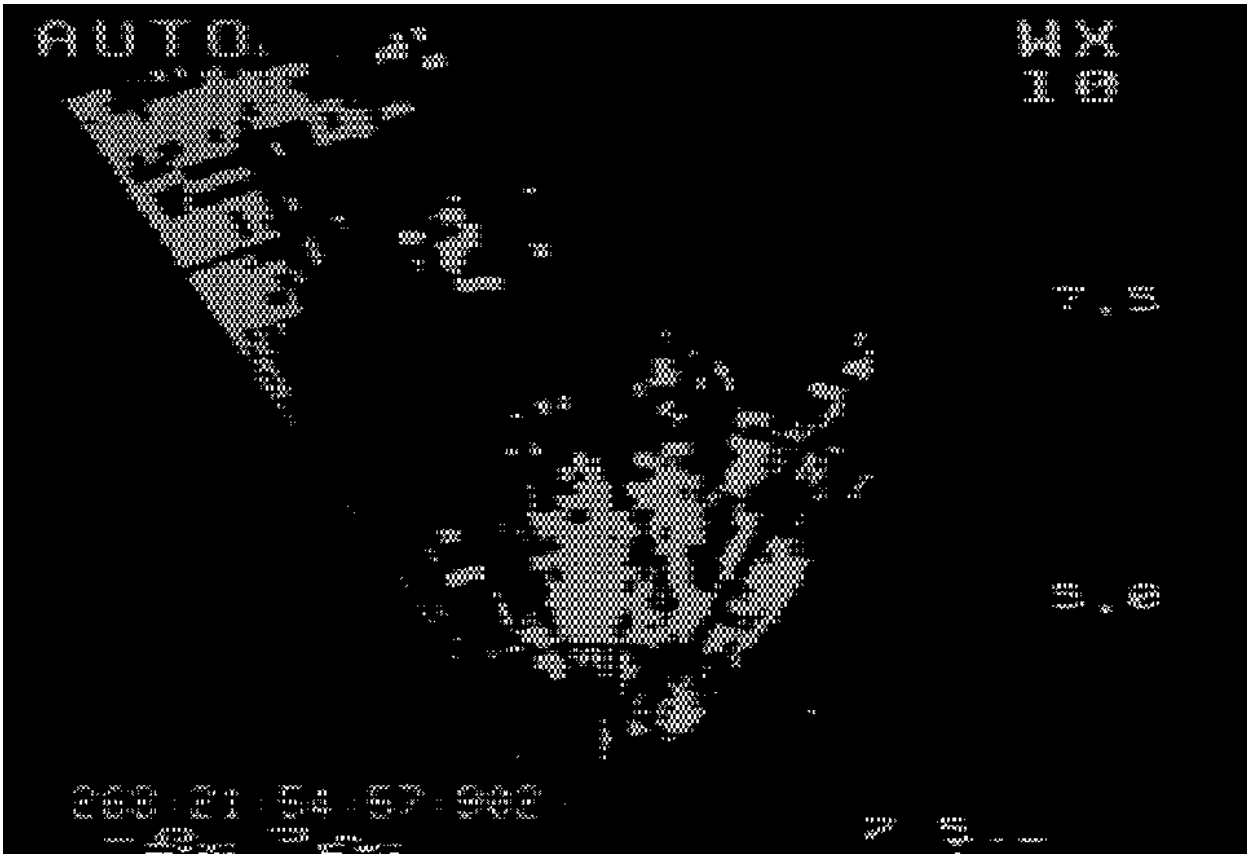

Figure 4. Light Rain, Often Below +23 dBz, on ARINC Color Weather Display

If the winds were uniform and homogeneous, the B scope Doppler map would consist of vertical stripes, with the spacing between bars determined by the wind speed. The color quantization is ± 2 m/sec centered on even ordinal numbers. A constant 9 m/sec wind on the nose would, over a ± 30° scan, decrease from the maximum to 7.8 m/sec at the azimuth scan edge producing a symmetric portrayal of blue with perhaps a narrow magenta stripe in the middle. The upper bar display indicates a gradient of increasing wind with range or altitude.

Figure 5 compares a graphical solution in azimuth x range display coordinates (B scope) along the elevation of the upper bar using linear winds in a trial and error "best fit" solution. The lower bar Doppler map, which is nearly uniformly blue, implies that there can be only modest horizontal shear. This, however, does not constrain the shear of the horizontal velocity components in the vertical dimension. The wind vector filed was modeled as follows:

(a) 8.8 m/s windspeed from 015 deg. right of nose
(b) 0 m/s vertical wind
(c) -0.5 m/s/km slope in the down range component in the vertical direction
(d) -4.3 m/s/km slope in the cross range component in the vertical direction
(e) -0.26 m/s/km shearing deformation
(f) +0.25 m/s/km stretching deformation
(g) 0 horizontal vorticity
(h) 0.33 m/s/km horizontal divergence

(i) -0.33 m/s/km slope in vertical component in vertical direction (conservation of mass flow)

(j) lower bar (see fig. 6) predominantly blue, with purple just beginning at right far edge and green/black along left

Alternatively, the solution may be expressed in a vector-matrix equation in Cartesian coordinates as

$$\begin{bmatrix} u(x,y,z) \\ v(x,y,z) \\ w(x,y,z) \end{bmatrix} = \begin{bmatrix} -2.3 \\ -8.5 \\ 0.0 \end{bmatrix} + \begin{bmatrix} 0.29 & -0.13 & -4.25 \\ -0.13 & 0.04 & -0.51 \\ 0.0 & 0.0 & -0.33 \end{bmatrix} \begin{bmatrix} x \\ y \\ z - z_0 \end{bmatrix}_{km}.$$

In figure 7, the linear model of wind vector field is plotted in a plan view showing the vector field along the upper bar elevation and the Doppler. At altitudes just above the aircraft (approx. 1000 ft. AGL.), the wind is more out of the northeast, decreasing in speed more so in the cross range component at lower altitude. The altitude span of the data is just about 5000 ft. The lower bar in the windshear mode operates with a clutter notch and will not generally display the lowest speeds. However, its correspondence is otherwise remarkable. Modeling by visual correspondence to the B-scope tends to emphasize the near range signature compared to, say, a PPI display or an area weighting, which would emphasize the farther range portions of the B-scope data.

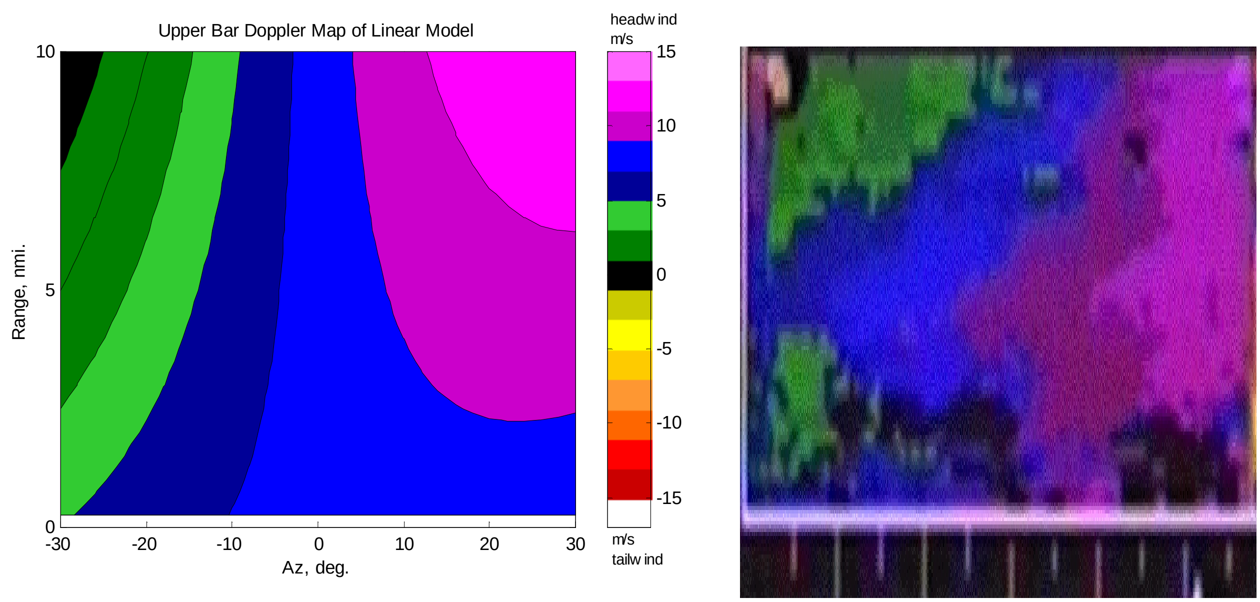

Figure 5 Side-by-Side Comparison of Upper Bar Doppler Map Data and Linear Wind Model

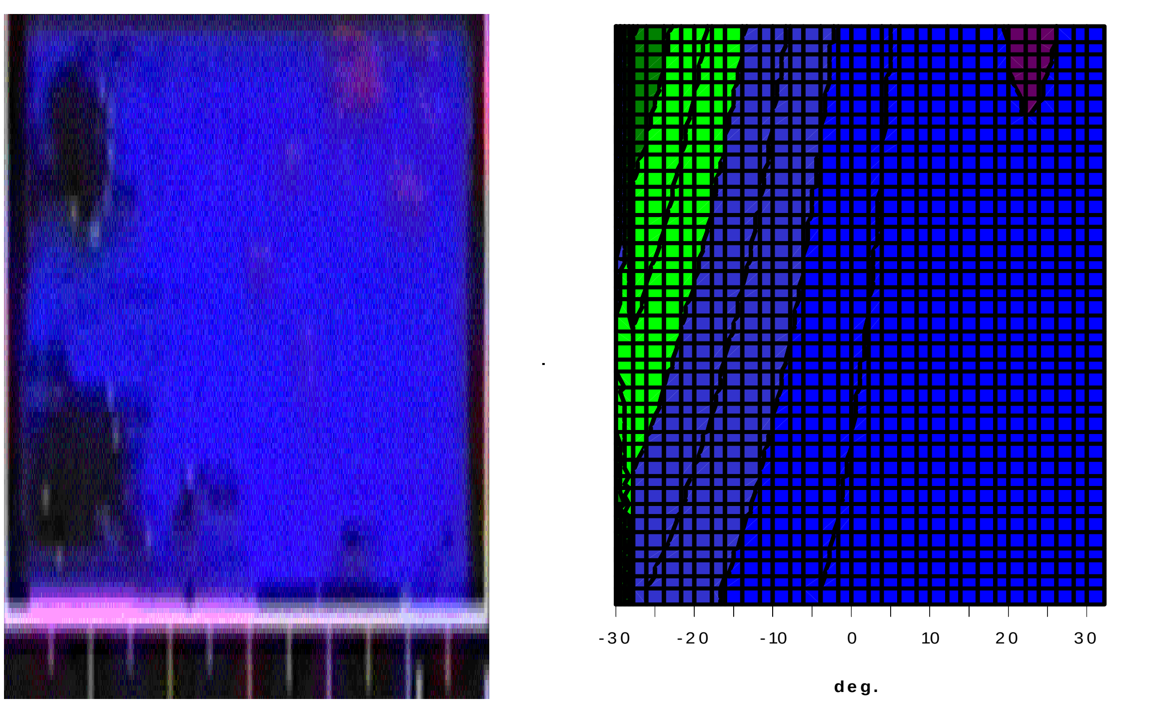

Figure 6 Side-by-Side Lower Bar Data and Linear Wind Model Doppler Maps

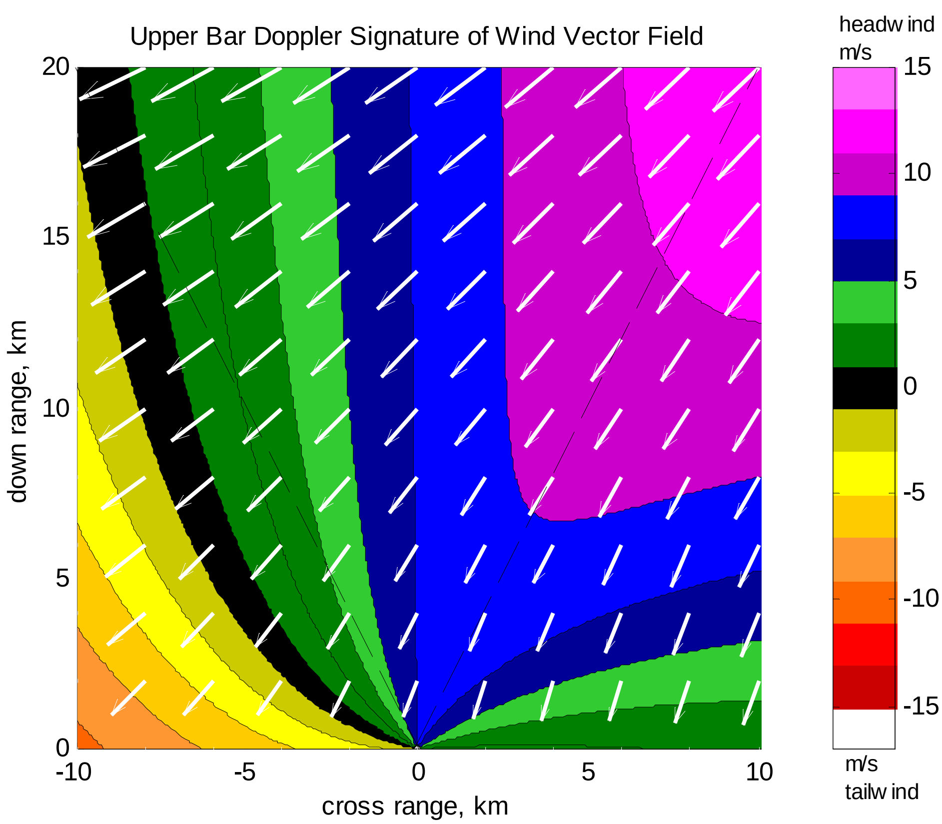

Figure 7 Upper Bar Cartesian Plan View of Doppler Map and (Horizontal) Linear Wind Vector Field

5.0 CONCLUSION

The effort to demonstrate and validate the ability of airborne RADAR to contribute to improved accuracy in airdrops will be initially addressed by computer modeling, where a notion of truth is accessible. The existing flight data that Northrop Grumman has captured is limited to low altitude encounters with mesoscale γ events in urban airport surroundings. The opportunity analyzed here represents an example of wide spread, very low reflectivity precipitation and should leave little doubt that a low power coherent airborne RADAR can estimate the winds.

This paper is unable to present any comparison with estimates of the wind field distribution at the time of sensor operation to substantiate accuracy. However, it has illustrated Doppler analysis in an example of low precipitation and compromised visibility, with an unknown wind field with apparent Doppler signature of a non-simple linear wind field. The analysis has been excersized with physical data showing how features of the Doppler signature relate to a smoothly varying wind.

A low power RADAR will always be challenged for range performance against targets with low RCS. However, many limitations in airborne RADAR arise from the limits of other backscatter, and any advantage of power greater than required to bring the interference above noise is dubious. The AN/APN-241 can, with waveform modifications for a higher duty cycle, obtain Doppler signatures from winds in the planetary boundary layer with particle size densities much less reflective than precipitation. The signal and data processing of existing equipment can be modified to interpret the signature of linear wind vector fields and provide that information to the aircrew.

Existing air delivery system practice does not utilize a profile of wind information – it uses input for wind vector fields along the flight path highly averaged, since only translation is considered. Emerging precision air drop technologies will improve upon the existing systems with algorithms which remove some simplifying assumptions in the wind as translation simplification and will require different information about the winds to control the guidance of low cost guided delivery systems.

At the long standoff ranges of the initial drop zone waypoint, the AN/APN-241 can provide a linear estimate of the variation of wind vector along the fall trajectory. At high altitudes, at those ranges, the beamwidth of the AN/APN-241 will begin resolving the drop altitude through several elevation bars. As the aircraft approaches the computed release point, the RADAR can update the winds with greater precision and utilize a different signature analysis, e.g. more like predictive windshear, as the altitude swath illuminated by the antenna beam shrinks with range and finer resolution in range is warranted. Current airdrop systems enter wind information manually. However, the real-time capture and utilization of wind sensor update rate data will revolutionize the precision air drop process.